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Precision of the Hall quantization in a naturally occurring two-dimensional system—HgCdMnTe bicrystals

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Abstract. A naturally occurring two-dimensional electron system—an inversion layer adjacent to a single grain boundary in narrow-gap diluted magnetic semiconductor $Hg_{0.79}Cd_{0.19}Mn_{0.02}Te$ ($E_g \leq 200$ meV)—was studied by means of quantum magnetotransport in magnetic fields up to 20 T and at temperatures down to 100 mK. Precise Hall quantization, plateau flatness down to 5×10^{-5}, as well as nearly vanishing longitudinal resistance minima, were observed. Detailed analysis of the data provided information on the bypass resistance and the homogeneity in the electron distribution.

1. Introduction

Diluted magnetic (semimagnetic) semiconductors have attracted much attention because of a dramatic modification of the semiconductor band structure by the sp–d exchange interaction between mobile electrons and localized magnetic moments [1]. It has been found, in particular, that the exchange coupling affects strongly both the longitudinal and Hall resistivities, especially near the metal–insulator transition [2, 3] and in the weakly localized regime [4, 5]. Furthermore, previous studies of magnetic materials showed that large spin polarization associated with this coupling, together with the spin–orbit interaction, resulted in the appearance of the so-called extraordinary Hall effect [6]. A question has then arisen as to whether the presence of impurity–spin and spin–orbit interactions, both specific to narrow-gap diluted magnetic semiconductors, could perturb the accuracy of quantization under the conditions of the quantum Hall effect (QHE), a timely problem in view of metrological applications of the phenomenon. Simultaneously, it has been found that two-dimensional (2D) inversion layers created by grain boundary defects in bicrystals of p-$Hg_{1-x}Mn_xTe$ and p-$Hg_{1-x-y}Cd_yMn_xTe$ are of adequate quality for the QHE to be observed [7]. Our work provides information on precision of the quantization and singles out extrinsic effects which affect the QHE in the studied system.

2. Samples and experiment

It has been known for a long time that ingots of mercury telluride and of its alloys with CdTe and MnTe, grown either by the Bridgmann or the solid state recrystallization method, consisted usually of several differently oriented single-crystalline grains of typical diameter 5–10 mm. Previous studies of such naturally occurring bicrystals, particularly of p-$Hg_{1-x}Mn_xTe$ [7–9], p-$Hg_{1-x-y}Cd_yMn_xTe$ [7] and p-$Hg_{1-x}Cd_xTe$ [10], have unambiguously demonstrated that defects associated with the grain boundary plane have donor character, and thus give rise to the presence of inversion layers in the p-type material. Surprisingly, electrons in these layers have relatively high mobility up to 5×10^4 cm^2 V^{-1} s^{-1}, presumably because of spatial correlation in positions of the defects.

The samples studied in the present work were cut from $Hg_{0.79}Cd_{0.19}Mn_{0.02}Te$ ingots grown by the solid state recrystallization method, as elaborated by Mycielski and Witkowska [11]. Deviations from stoichiometry, and thus the type of the conductivity, were controlled by mercury partial pressure during the growth process. The temperature dependence of the Hall coefficient measured for the reference single-crystalline samples showed that the studied material contained about 10^{16} acceptors/cm^3, which trapped holes below 20 K, so that the sample resistance became as high as 60 MΩ at 4.2 K. Optical

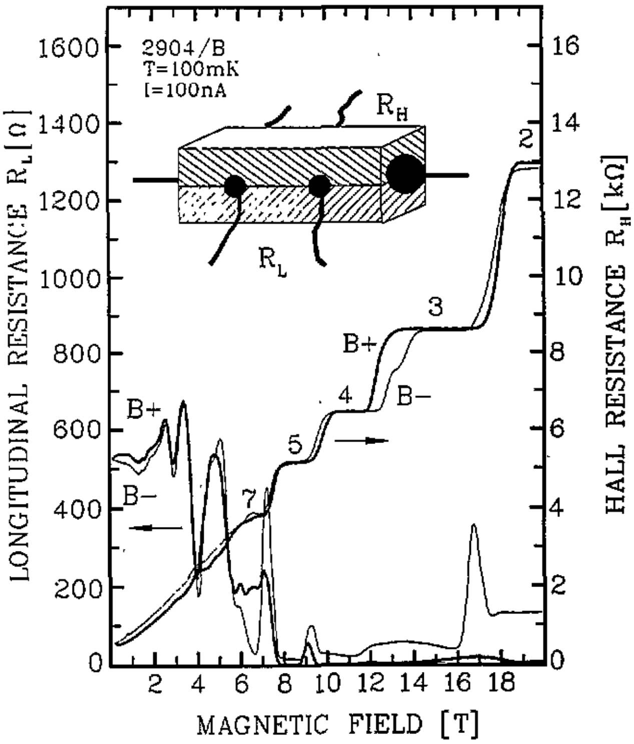

Figure 1. Longitudinal and Hall resistances at 100 mK of an HgCdMnTe bicrystal with 2D electron concentration $N_S = 1.1 \times 10^{12}$ cm^{-2} for two directions of the magnetic field (B_+ thick curves, B_- thin curves). Sample dimensions: distance between lateral probes $L = 0.7$ mm, width $W = 0.5$ mm. Inset: schematic view of the sample with a single grain boundary prepared for transport measurements.

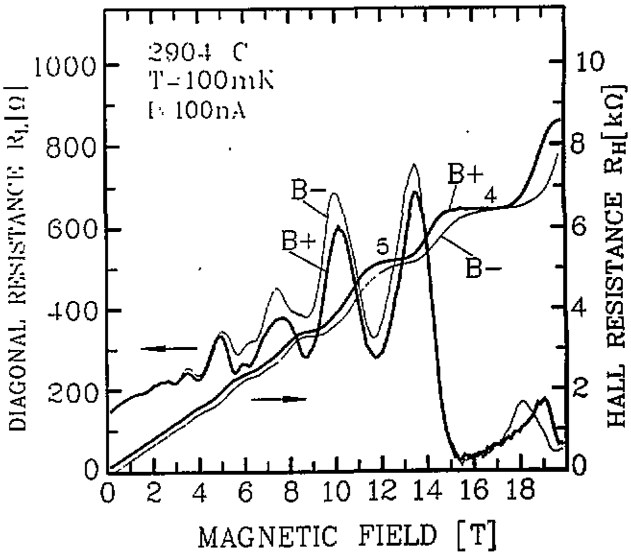

Figure 2. Longitudinal and Hall resistances at 100 mK for an HgCdMnTe bicrystal with higher 2D electron concentration $N_S = 1.76 \times 10^{12}$ cm^{-2}. Sample dimensions: $L = 0.70$ mm, $W = 0.80$ mm.

transmission measurements pointed to an energy gap of about 180 meV, a value in accord with that expected from the nominal alloy composition. The bicrystalline samples were prepared in the form of the Hall bars with the largest surface parallel to the grain boundary plane, as shown in the inset to figure 1. Six gold leads were soldered with indium, providing low-noise contacts to the inversion layer. For magnetotransport measurements, the samples were mounted in a dilution refrigerator installed in a Bitter coil capable of producing magnetic fields up to 20 T.

3. Results and discussion

The longitudinal R_L and Hall R_H magnetoresistances at 100 mK for the bicrystal with 2D electron density $n_S = 1.1 \times 10^{12}$ cm^{-2} are shown in figure 1. The data were taken for two directions of the perpendicular magnetic field, denoted as B_+ and B_-. Deep minima in R_L and the corresponding QHE plateaux with quantum indices $i = 7, 5, 4, 3$ and 2 are clearly visible. The absence of the plateau with the quantum index i = 6 can be understood taking into account the multisubband character of our 2D system [12]. The lack of certain plateaux is a consequence of the overlap between the Landau levels originating from different subbands [13]. The same set of data for a sample with $n_S = 1.76 \times 10^{12}$ cm^{-2} is presented in figure 2. Due to the higher concentration value, only quantum indices down to $i = 4$ were observed in the accessible magnetic field range.

According to previous QHE studies [14, 15] the current path distributions in a sample are different from the two directions of the magnetic field, and therefore, a comparison of the data for B_+ and B_- provides information on the macroscopic homogeneity of the 2D electron gas. Since for both presented samples QHE plateaux and R_L minima occur in approximately the same field range, the concentration gradient is relatively small. This has been confirmed by the observation of the low-field Shubnikov–de Haas oscillations, which are well resolved up to the Landau level index $n \approx 15$. We estimate that the macroscopic concentration fluctuations in our samples do not exceed 6% of the mean value.

As one can see from figures 1 and 2, the R_L minima show non-zero values $R_L^{min} > 0$. The magnetoresistance oscillations are superimposed on the monotonically increasing background (figure 3). The background resistance is proportional to the square of the magnetic field, $R_L^{min} = CB^2$. The proportionality factors C were found to depend on the magnetic field direction of the contact pair. It was noted by von Klitzing and Ebert [14] that such an effect resulted from the presence of electrical bypass between contact probes. From experimentally obtained coefficients C one can estimate the values of the bypass resistances R_X. For the sample presented in figure 1 we estimated $R_X = 1.5$ MΩ for one current path distribution corresponding to B_- and $R_X = 25$ MΩ for B_+. Lack of temperature dependence of R_X at $T < 0.5$ K indicates that the bypass resistances have a metallic character. The values of R_X quoted above are considerably smaller than those suggested by the resistance measurements on the reference single-crystalline sample ($R \gg 25$ MΩ). This may indicate that the presence of the

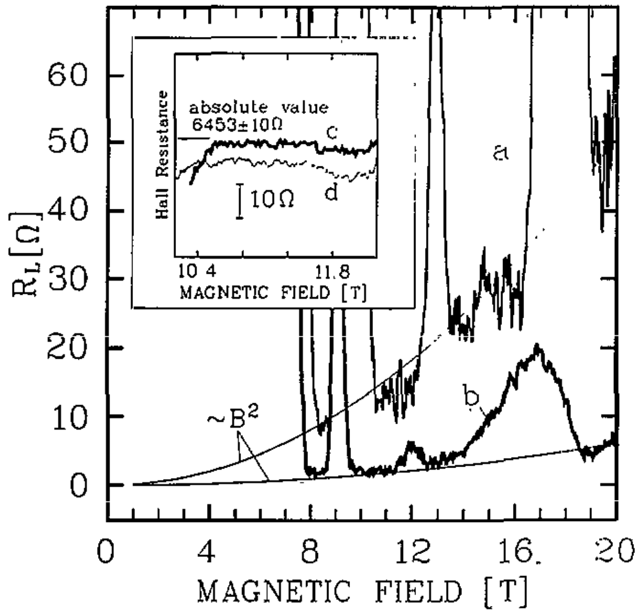

Figure 3. Field dependence of the longitudinal resistance in a magnified scale showing residual resistance in the R_L^{min} for different contact pairs (curves a and b). Inset: detailed picture of the Hall plateaux corresponding to quantum index $i = 4$, measured for different contact pairs (curves c and d).

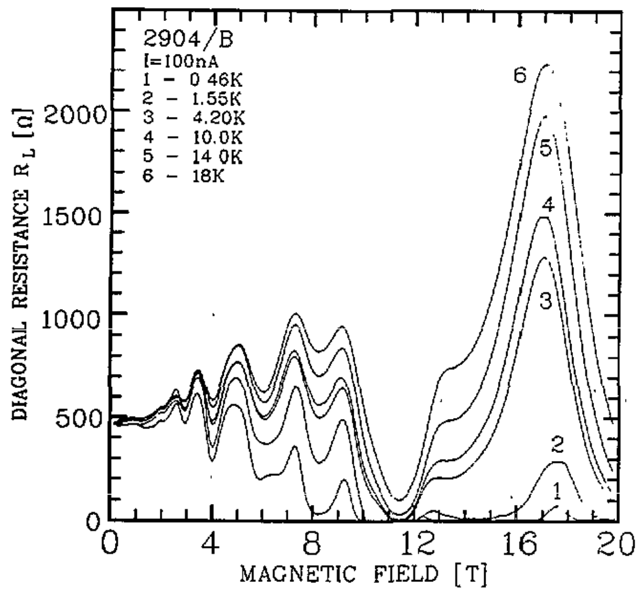

Figure 4. Longitudinal magnetoresistance R_L measured on HgCdMnTe bicrystal at different temperatures.

short-circuiting path is related in some way to the existence of the grain boundary.

The presence of finite bypass resistances just discussed is, at present, the main factor limiting precise measurements of the Hall quantization in our system. It has been established that the deviation from the exact quantized value is given by

$$\Delta R_H = \alpha R_L^{min} \qquad (1)$$

where the dimensionless factor α is of order unity. Figure 3 illustrates the accuracy of the Hall quantization in our sample for the plateau corresponding to the quantum index $i = 4$. Because the bypass resistance assumes random values one expects different deviations from the quantized values for different contact pairs. This effect is clearly seen in figure 3 (inset). Using a standard laboratory equipment we were able to establish that the absolute resistance at the plateau agrees with the theoretical value with the accuracy of about 0.1%. On the other hand, the relative slope of the plateau has been established to be as little as 5×10^{-5} of the total Hall resistance over the distance of 1 T.

Temperature evolution of the field dependence of R_L and R_H are collected in figures 4 and 5. It should be recalled that above 20 K the inversion layer conductance is short-circuited by the bulk. As one can see from figure 4, the overall magnitude of R_L tends to increase with the temperature. In the temperature range $1\ \mathrm{K} < T < 20\ \mathrm{K}$ and for the magnetic field $B > 7$ T it exhibits an activated behaviour

$$R_L(B) \sim \exp(-E(B)/kT). \qquad (2)$$

We have found that activation energy $E(B)$ corre-

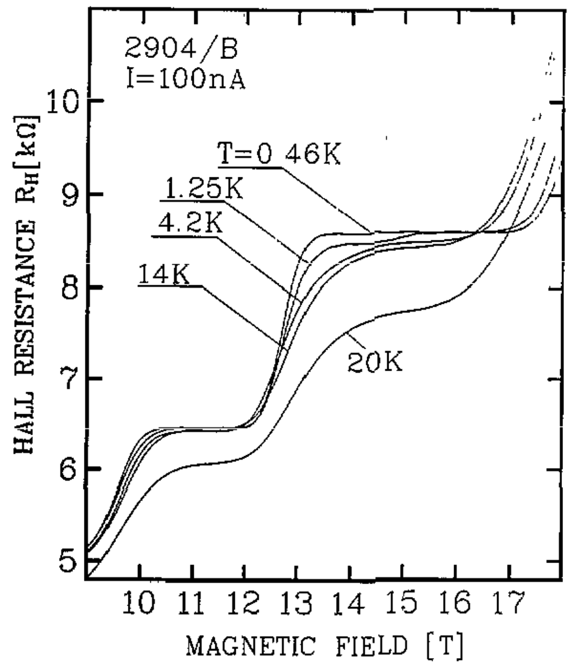

Figure 5. Temperature evolution of the Hall resistance R_H plateaux for the magnetic field range corresponding to quantum indices $i = 4$ and $i = 3$. At $T = 20$ K parallel bulk conductance leads to visible diminishing of R_H values.

sponding to quantum index $i = 4$ ($B = 11.4$ T) is about 6 meV, while that for $i = 3$ ($B = 15.2$ T) is ten times smaller $E(B) \approx 0.5$ meV. Similar numbers follow from the temperature dependence of the Hall plateau slopes $\Delta R_H/\Delta B$ shown in figure 5. A large difference between the two quoted activation energies indicates that—contrary to the ordinary narrow-gap semiconductors—the spin-splitting energy is much smaller than half of the cyclotron energy. This points to the compensation of the electron orbital momentum by the s–d exchange contribution to the spin splitting.

4. Summary

Our results demonstrate that in a naturally occurring 2D system of a narrow-gap diluted magnetic semiconductor the accuracy of the quantization of the Hall resistance is better than 0.1%. Further reduction of the error bar requires elimination of the presence of electrical bypass. The activation energy of the resistivity suggests the influence of the s–d interaction upon the spin splitting of the Landau levels.

Acknowledgments

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